Report for 2003AZ18B: Impacts of Conservation Measures and Alternative Water Supplies on Groundwater

- unclassified:
    - Springer, A.E. and J.A. Kessler. 2003. Groundwater model of the Redwall-Muav aquifer of the Coconino Plateau incorporating impacts of pumping and water conservation on small springs of the Grand Canyon. Annual meeting of the Geological Society of America, November 2-5, Seattle, WA.

Report Follows

A. Problem and Research Objectives:

Conservation of water and the use of alternative water supplies have become very important tools for water managers. The broad category of water conservation may include water efficiency, wise-water use, or curtailment of use (Pinkham and Davis 2002). Alternative supplies of water include graywater reuse, water recycling, rainwater harvesting, or wastewater reclamation and reuse. Alternative water supplies are a way to augment water supplies after the application of conservation measures and are an extremely important tool to overall water management.

Outside of Arizona's Active Management Areas (AMAs), the issues of conservation and alternative water supplies are becoming more important. Such recent issues as Canyon Forest Development, snowmaking with reclaimed City of Flagstaff wastewater, private wastewater treatment versus municipal wastewater treatment systems in rural areas and other issues have pointed out how few scientific tools water managers have to make these decisions.

Canyon Forest Village proposed to provide 10 percent of their water supply through rain harvesting and potentially another 20 percent or more of their water through reuse of reclaimed water (Grahl 2000). No predictions were made of the fate of these alternative water supplies and/or potential impacts to recharge to the underlying aquifers or runoff on nearby streams. Groundwater models built to predict the impacts of this community did not have scenarios to predict the impacts of these alternative water supplies on local springs in the Grand Canyon.

A model built to predict the impacts of safe yield and sustainable yield on a rural groundwater basin undergoing rapid conversion to residential noted the important roles of private wastewater system (septic) return flow to the aquifer (Navarro 2002). Predictions of future water use scenarios did not address the potential differences in recharge to the aquifer that graywater reuse would cause the aquifer.

In Tucson, effluent use currently meets about 5 percent of municipal water demand (Gelt and others 1999). As much as 31 percent of Casa del Agua's (an Arizona experimental home built in 1989 and used for water research conservation since then) total water budget is from recycled graywater. It is not known the fate of these alternative supplies of water on the local aquifer budgets (Gelt 1993).

This report addresses the impact of conservation measures and alternative water supplies on groundwater budgets. Conservation measures are described quantitatively in terms of their impact on the water budget, and the construction of a series of generic groundwater models allowed for the quantitative evaluation of alternative water supplies at the regional level. In addition, a specific northern Arizona groundwater model was adjusted to consider water conservation practices. The objectives of this research were:

1. To quantify the impacts of different conservation measures on groundwater budgets.

2. To develop generic groundwater models to understand the impacts of different alternative water supplies on groundwater budgets.
3. To determine the impacts of conservation measures on a calibrated groundwater flow model of a specific aquifer.
4. To determine the impacts of alternative water supplies on a calibrated groundwater flow model of a specific aquifer.

Impacts of Conservation Measures on Groundwater Budgets

A thorough review and compilation of existing published data was conducted to quantify the impacts of water conservation and available alternative water supplies in Arizona. The results of this literature review are presented in table 1.

Table 1. Water conservation measures and alternative water supplies available in the State of Arizona. This table includes published data regarding the quantitative effects these measures have on water budgets. Data was collected from resources specific to Arizona and the desert Southwest.

Water Conservation Measure	**Water Budget Impact of Applied Conservation**	**Seasonality of Impact**	**Source**
Water Use Reduction			
Note: In 1990, 4.6 m^3/day supplied a 5 person household. In 2000, 3.4 m^3/day supplied a 5 person household. General water use education has led to a reduction of up to a 25 percent in personal water use between 1990 and 2000. Sources: Arizona Department of Water Resources (ADWR); United State Environmental Protection Agency (EPA)			
Low-flow appliances			
Showerheads	Rated flows: 27 to 44 m^3/d → 4 to 14 m^3/d; average 70% reduction in water use	Year-round	Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA)
Toilets	Rated flows: 13-18% reduction in water use	Year-round	SAHRA
Faucets	Rated flows: 15 to 27 m^3/d → 8 to 14 m^3/d; average 50% reduction in water use	Year-round	SAHRA
Dishwashers	Rated flows: .05 to .1 m^3/d → .03 to .04 m^3/d; average 47% reduction in water use	Year-round	SAHRA

Water Conservation Measure	Water Budget Impact of Applied Conservation	Seasonality of Impact	Source
Washing Machine	Rated flows: 0.15 m^3/load → 0.1 m^3/load; 33% reduction in water use	Year-round	SAHRA
Efficient Yard Practices			
Graywater Use (dual plumbing systems)	0.13 to 0.17 m^3/d out of septic/sewer system	Mar. to Nov.	SAHRA; Whitney et al 2004
Xeriscaping (preservation of native landscape)	Reduction of irrigation volume by 50% or more	Mar. to Nov.	Arizona Department of Water Resources (ADWR)
Choose spa over pool	0.24 m^3/d → 0.06 m^3/d; 75% reduction in water use	Summer	SAHRA
Pool and/or spa cover	ET reduction by 95%	Summer	SAHRA
Recirculating water features in shade	Unknown (reduction in ET varies)	Summer	SAHRA
Increased Recharge			
Artificial Recharge/ Storing surface water in the aquifer (from CAP, effluent, & Salt/Verde River water)	Phoenix: 966,470 m^3/d (1999); 15,949 m^3/d (2001) stored in aquifer	Nov. to Mar.	ADWR - Phoenix AMA
	Tucson: 174,118 m^3/d (1999) stored in aquifer	Nov. to Mar.	- Tucson AMA
	Prescott: 222,446 m^3/d (1999) stored in aquifer	Nov. to Mar.	- Prescott AMA
	Pinal: 6,895 m^3/d (1999); 1,588,477 m^3/d (2000) stored in aquifer	Nov. to Mar.	- Pinal AMA
	Wastewater reclamation in Florida resulted in modeled increases to the water table of ~ 13 m; Modeled results of recharge in Mojave	Nov. to	O'Reilly 2002; Izbicki & Stamos 2003

Water Conservation Measure	Water Budget Impact of Applied Conservation	Seasonality of Impact	Source
	Desert, CA show water table increases of 3-30 m over a 20 year drought period.	Mar.	
Rain gardens	Rain gardens most effective when 10% the area of impervious surface in the model. Increasing rain garden area to >20% saw very little increased recharge.	Nov. to Mar.	Potter 2002
Reducing impervious surface from 18% to 2%	Increase stream baseflow 20%; Decrease surface runoff 90%; Increase regional groundwater flow 10%; Increase spring flow 5%	Year-round	Bannerman 2000
Alternative Water Sources			
Surface Water	Tucson: 676 m^3/d (1998)	Year-round	ADWR - Tucson AMA
Rain Harvesting	Two buildings in Tucson generate 0.15 m^3/d; Casa del Agua in Tucson collects 75% of annual precipitation that falls on its catchment area (14 m^3/year on 55.7m^2 area)	Snowmelt & Monsoon	City of Tucson Water Harvesting Guidance Manual; Gelt 1993 (Casa del Agua)
Reclaimed water	Tucson: 37,655 m^3/d (1998) ~ 311,129 m^3/d water used on AZ Central Valley golf courses	Year-round Mar. to Nov.	ADWR - Tucson AMA McKinnon 2002
Importation of groundwater from other groundwater basins	Tucson: 0 m^3/d (1998)	Year-round	ADWR - Tucson AMA

Impacts of Alternative Water Supplies on Groundwater Budgets

A generic aquifer was created to represent typical hydrologic characteristics for the State of Arizona. A generic water budget was then produced for this aquifer. The range in potential alternative water supplies were defined for use in the numerical modeling process based on this theoretical aquifer.

Generic Aquifer Characteristics

The following general aquifer descriptions have been taken from a literature review of regional and local hydrogeology. Basin and Range aquifers were stressed because most Active Management Areas (AMAs) in Arizona are located in this type of setting.

- Basin and Range aquifers are the principal source of groundwater in Southern Arizona. The aquifers are present in alluvium-filled basins between mountain ranges (Robson and Banta 1995).
- The regional aquifer in the Pinal Creek Basin (Pinal AMA) is made up of unconsolidated stream alluvium and consolidated basin fill (Angeroth 2002).
- The land surface of the basins generally slopes gently from the adjacent mountain fronts toward the flat-lying central parts of the basins (Robson and Banta 1995).
- Thickness of basin-fill is not well constrained, but ranges from 330 to 1600 m in many basins (Robson and Banta 1995).
- The hydraulic conductivity of alluvium has been measured in the Pinal Creek Basin to be 3-200 m/day, and the basin fill hydraulic conductivity was measured to be 0.5-250 m/day (Angeroth 2002).

A conceptual aquifer was constructed based on the information mentioned above. This aquifer has the following characteristics:

- Conceptual AMA area is 10.01 km^2, (100,200,100 m^2)
- Unconfined Aquifer
- Composed of homogenous and isotropic mix of alluvium and/or basin fill
- Thickness of 465 meters.
- Average hydraulic conductivity of 1 m/day
- Line of constant head (964 m) on the west side of the model, to represent the higher elevation of recharge occurring along a mountain front.
- Line of drains (930 m) simulating a seep face on the east side of the model, and representing the slope of a basin fill aquifer away from mountain ranges.

Generic Water Budget Characteristics

The following general water budget descriptions have been taken from a literature review of regional and local hydrogeology:

- Recharge to Basin and Range aquifers occurs primarily as precipitation in the mountains surrounding the aquifer. Only approximately 5 percent of precipitation that falls recharges the aquifer. Average mountain precipitation is 0.4 m/year (Robson and Banta 1995). Average precipitation in Arizona is .322 m/year (8.82 x 10^{-4} m/day) (National Climatic Data Center 2003).
- Some aquifer recharge occurs from irrigation of commercial crops, golf courses and other vegetation, and from percolation out of reservoirs, canals and sewage treatment plants. Between 1915 and 1980, about half of the water pumped from Arizona aquifers ended up going back into the ground as recharge from irrigation (Robson and Banta 1995).
- Underflow flow can be a significant component of recharge in some basins (Robson and Banta 1995).
- Most precipitation is lost to evapotranspiration. Evapotranspiration also depletes groundwater where the water table is very shallow (Robson and Banta 1995).
- Groundwater leaves the aquifers as discharge to streams and springs, underflow, and withdrawal by wells (Robson and Banta 1995).
- Roaring Springs pumps approximately 3700 m^3/day, and about 1300 m^3/day (35 percent) is processed at the Grand Canyon wastewater treatment plant (Mack 2003).
- The major wells supplying Tusayan, Arizona with water have a pumping capacity of approximately 1200 m3/day, and about 530 m3/day (45 percent) is processed at the Tusayan Wastewater Treatment Facility (Petzold 2003).

An initial conceptual water budget was constructed based on the information mentioned above. The volumes in this budget are subject to change with different management practices.

Table 2. Conceptual water budget for a generic basin-fill aquifer in Arizona.

Water Budget Component	Value	Vol. in Conceptual AMA
Precipitation	8.82 x 10^{-4} m/day	88,200 m^3/day
Natural Recharge	~5% Precipitation	4,410 m^3/day
Artificial Recharge	0% to 50% of pump vol.	0 to 4410 m^3/day
Evapotranspiration	~95% Precipitation	83,790 m^3/day
Pumping	Natural Recharge + Artificial Recharge	4,410 to 8,820 m^3/day
Spring Flow	Unknown – Variable	Defined by modeled potentiometric surface

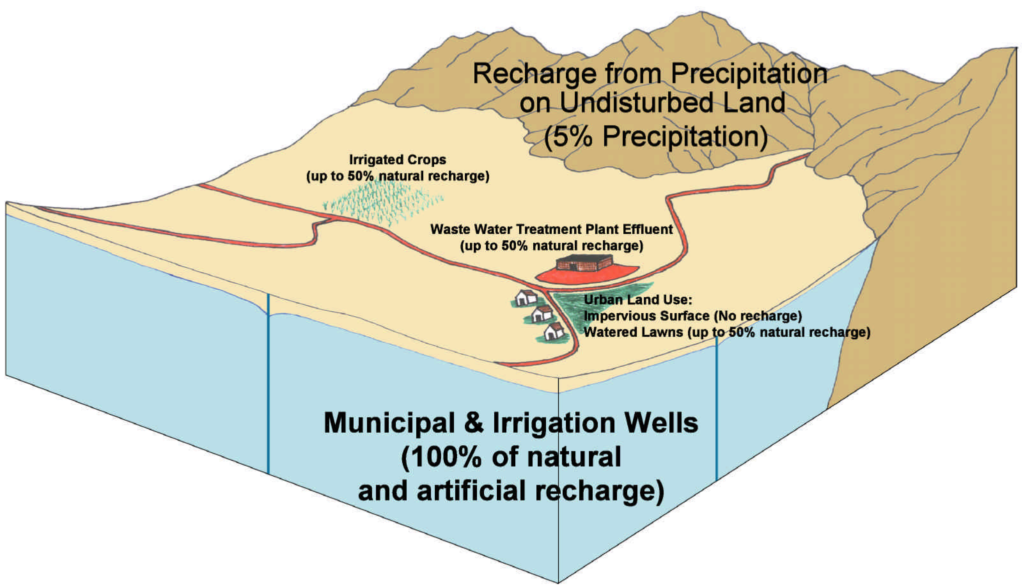


Figure 1. Conceptual model of theoretical basin-fill Arizona aquifer and associated land use.

B. Methodology

It was our objective to assess the impact of alternative water supplies on a theoretical Arizona aquifer under the constraints of Arizona's Safe-Yield policy. *Safe Yield is defined as the hydrologic concept of achieving and maintaining a long-term balance between the annual amount of groundwater withdrawn in an AMA and the annual amount of natural and artificial recharge in the AMA*. We assumed in this modeling process that water-use reduction practices, such as personal wise water use, installation of water efficient appliances, and effective infrastructure building and maintenance are balanced by the increasing water needs of a growing population. The alternative water supplies we explored are most commonly implemented after more traditional conservation practices are in place. In this project, we examined the impacts of irrigating crops and lawns with wastewater treatment plant effluent and rainwater harvesting.

The model variables we used to assess impacts of different water management scenarios were well pumping rates, recharge rates, spring discharge rates, changes in aquifer storage, and changes in the potentiometric surface of the aquifer. As stated above, the upper bound on pumping was constrained by the Safe Yield policy. In addition, the upper bound on artificial recharge rates was constrained by pumping rates. The models were calibrated based on an estimate of WWTP effluent volume of 25 percent of pumping volume.

Thus, the general mathematical form of the management objective was:

$P = N + xP + yP + zR$

Where:

- P = Annual average total volume of water pumped from all wells in the aquifer study area
- N = Annual volume of water that naturally recharges the aquifer in the study area (some average percentage of precipitation)
- R = Annual average volume of water that falls as precipitation on rainwater harvesting collection areas in the study area
- x = Annual average percentage of water pumped from the aquifer that is discharged as effluent from the study area's waste water treatment plant directly into the environment (in a natural channel, for example)
- y = Annual average percentage of water pumped from the aquifer that is discharged as effluent from the study area's waste water treatment plant for use on irrigated lawns and/or crops
- z = Annual average percentage of water harvested in rainwater collection areas that is discharged to the aquifer (as irrigation)

A description of five management scenarios based on the general management objective follow. These scenarios were used to create numerical models which were calibrated and then compared to quantitatively describe the effects large-scale water conservation and alternative water supplies can have on Arizona's Basin and Range-type aquifers.

<u>Management Objective 1</u>:

$P = N + xP + yP + zR$; where $x = 25\%$, $y = 0\%$, $z = 0\%$

Design a pumping scenario that 1) *does not* include irrigation of crops and lawns with waste water treatment plant effluent, and 2) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. The first estimate of annual artificial recharge is 25 percent of annual pumping, and represents wastewater treatment plant discharge to the environment along a channel.

<u>Management Objective 2</u>:

$P = N + xP + yP + zR$; where $x = 0\%$, $y = 25\%$, $z = 0\%$

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste water treatment plant effluent, and 2) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. This scenario will distribute wastewater treatment plant discharge (25 percent of annual pumping) over an irrigated area.

Management Objective 3:

P = N + xP + yP + zR; where x = 0%, y = 25%, z = 10%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 10 percent of rainwater harvested from impervious surfaces and reclaimed waste water (25 percent of annual pumping) are both used to irrigate urban and agricultural areas.

Management Objective 4:

P = N + xP + yP + zR; where x = 0% and y = 25%, z = 100%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces and reclaimed waste water (25 percent of annual pumping) are both used to irrigate urban and agricultural areas.

Management Objective 5:

P = N + xP + yP + zR; where x = 25%, y = 0%, z = 100%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces was applied as irrigation to urban and agricultural areas, and reclaimed waste water (25 percent of annual pumping) was discharged to the environment along a channel.

Management Objective 6:

P = N + xP + yP + zR; where x = 0% and y = 0%, z = 0%

Design a pumping scenario that 1) *does not* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) *does not* include harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces and all reclaimed waste water are recycled and never discharged to the environment.

1.1. Generic Numerical Flow Modeling

After defining the conceptual model's hydrologic characteristics, water budget components, and management objectives to be tested, a generic numerical groundwater flow model was built. This model was used to simulate the effects of the previously-defined range of conservation measures and alternative water supplies during a 100-year time period. Simple graphics were created to display the cumulative changes to the water budgets through time, and the impacts of different management scenarios were quantified.

Numerical Groundwater Flow Model Construction

Model Software:

Groundwater Vistas Version 3.47 (Environmental Simulations, Inc. Reinhold, PA), a Windows model-independent graphical user interface for the 3-D groundwater flow model MODFLOW.

Model Dimensions:

Horizontal Grid:

Number of Rows: 572
Number of Columns: 572
X spacing: 17.5 meters
Y spacing: 17.5 meters
Total Model Cells: 327184

Vertical Grid:

Number of Layers: 1
Model Bottom Elevation: 500 meters above sea level
Model Top Elevation: 965 meters above sea level
Layer is flat

Default Parameter Values:

Aquifer is isotropic, homogenous
Hydraulic Conductivity: 1 m/d
S, S_y, Porosity: all 0.02 (Fetter 2001)

Time Steps:

10 Stress Periods, each stress period 3650 days
10 Time Steps per Stress Period

Solver:

Preconditioned Conjugate Gradient Solution Package, Version 2.1
Iteration seed computed by: MODFLOW
Max. # Iterations: 1000
Iteration Parameters: 5
Head Change criterion for convergence: 0.001

Boundary Conditions:

- No-flow boundary on the north and south sides of the model
- Constant head boundary on the east side of the model (964 m)
- 16 Wells (Constant Flux) are evenly distributed throughout the center of the model. Wells are all located at least 1000 m from boundary conditions. For each water use scenario modeled, the pumping rates were adjusted to balance that scenario's recharge rates. The range of pumping rates used in this project is 4339.4 m^3/d (271.2 m^3/d per well) to 8704 m^3/d (544 m^3/d per well).
- Line of 572 Drains (Head-dependent flux) along east side of model at an elevation of 930 m. Drain conductance is 8.75 x 10^3.

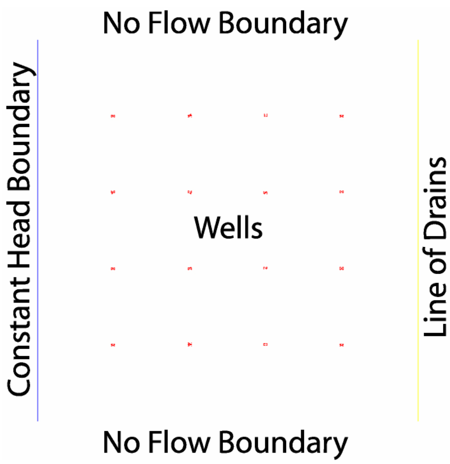


Figure 2. Spatial distribution of boundary conditions in generic numerical groundwater model.

Recharge Zones:

The distribution of recharge zones in the numerical groundwater model was based on the average state-wide distribution of land use in Arizona. 0.5 % of the area is rural roads, 2 % is urban, 61 % is natural, and 37 % is non-irrigated agriculture (US Census Bureau 2004).

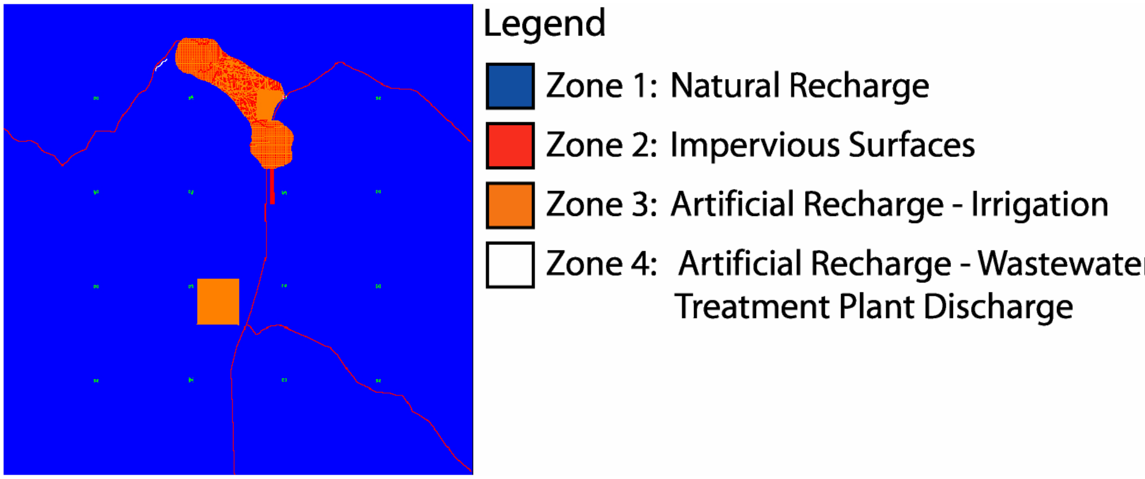
Zone 1: Natural Recharge. This zone represents areas of predominantly natural vegetation, with recharge rates of 5 % of precipitation, or 4.41 x 10^{-5} m/day.

Zone 2: Impervious surfaces. This zone represents land uses that include building roofs, roads, and parking lots. The recharge rate for this zone is 0.00 m/day.

Zone 3: Artificial Recharge/Irrigation. This zone includes lawns and irrigated fields. This recharge rate varies between 5 % of precipitation (4.41 x 10^{-5} m/day) and 5.21 x 10^{-4} m/day.

Zone 4: Artificial Recharge/Wastewater Treatment Plant Discharge. This zone represents the area that may receive discharge from a wastewater treatment plant. This recharge rate varies between 5 % of precipitation (4.41 x 10^{-5} m/day) and 50 % of maximum pumping (0.220 m/d).

Figure 3. Spatial distribution of recharge zones in a generic numerical groundwater model of an Arizona basin fill-type aquifer.



Description of Management Objective Variables

The following table summarizes the areas and volumes of water used by each source and sink in the generic numerical groundwater flow model (Table 3).

Table 3. Summary of values used in each numerical groundwater management model for a generic basin-fill aquifer in Arizona.

Scenario	Pump Rate (m^3/d)	Zone 1 Recharge	Zone 2 Recharge	Zone 3 Recharge	Zone 4 Recharge
Management Objective 1: $P = N + xP + yP + zR;$ $x = 25\%$ $y = 0\%$ $z = 0\%$	***Per Well:*** 362.50 ***Total:*** 5,800	***Area (m^2):*** 98701618.75 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00	***Area (m^2):*** 8575 Value (m/d): 0.17
Management Objective 2: $P = N + xP + yP + zR;$ $x = 0\%$ $y = 25\%$ $z = 0\%$	***Per Well:*** 363.29 ***Total:*** 5812.64	***Area(m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 Value (m/d): 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 5.71×10^{-4}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 3: $P = N + xP + yP + zR;$ $x = 0\%$ $y = 25\%$ $z = 10\%$	***Per Well:*** 373.50 ***Total:*** 5,976	***Area (m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 6.34×10^{-4}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 4: $P = N + xP + yP + zR;$ $x = 0\%$ $y = 25\%$ $z = 100\%$	***Per Well:*** 472.00 ***Total:*** 7552	***Area (m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 1.21×10^{-3}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 5: $P = N + xP + yP + zR;$ $x = 25\%$ $y = 0\%$ $z = 100\%$	***Per Well:*** 472.00 ***Total:*** 7,552	***Area(m^2):*** 95944756.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 5.21×10^{-3}	***Area (m^2):*** 8575 ***Value (m/d):*** 0.22
Management Objective 6: $P = N + xP + yP + zR;$ $x = 0\%$ $y = 0\%$ $z = 0\%$	***Per Well:*** 271.20 ***Total:*** 4339	***Area (m^2):*** 98710193.75 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00

Graphical Illustration of Model Results

Natural Environment:

P = N + xP + yP + zR; where x = 0%, y = 0%, and z = 0%

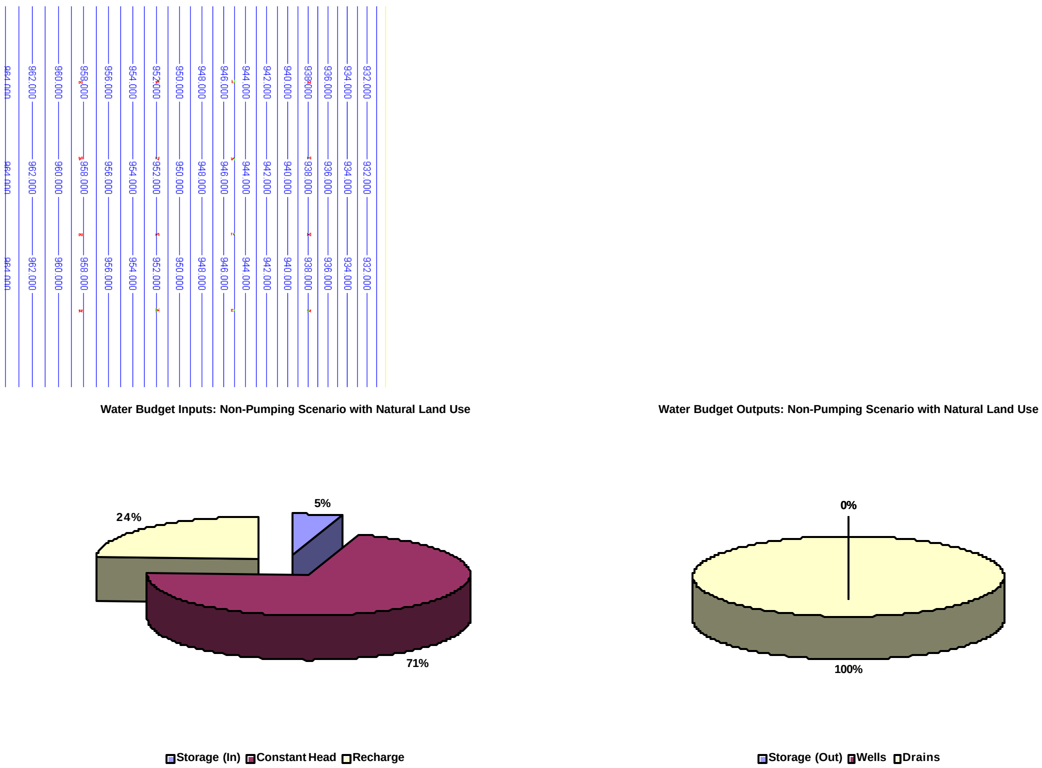
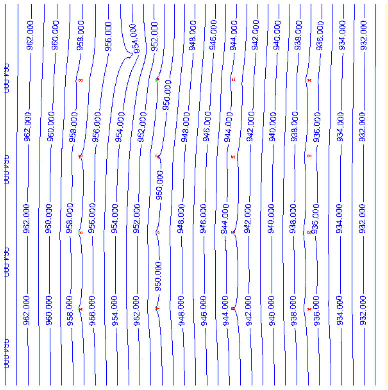
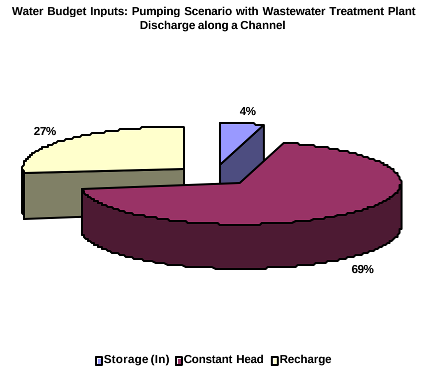


Figure 4. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under natural conditions (i.e. no pumping, irrigation or impervious surfaces).

Management Objective 1:

P = N + xP + yP + zR; where x = 25%, y = 0%, and z = 0%





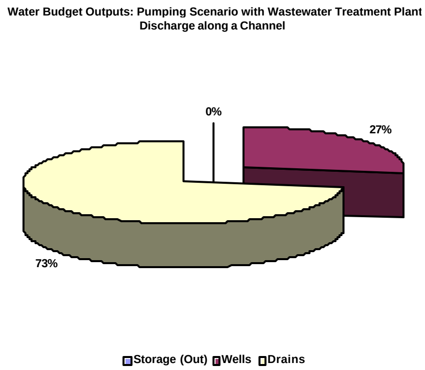
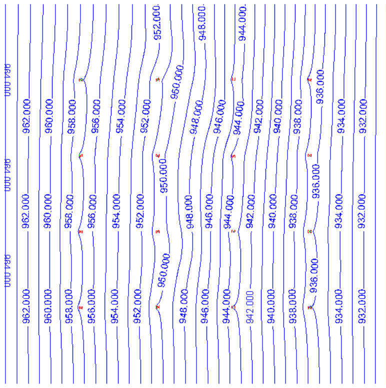
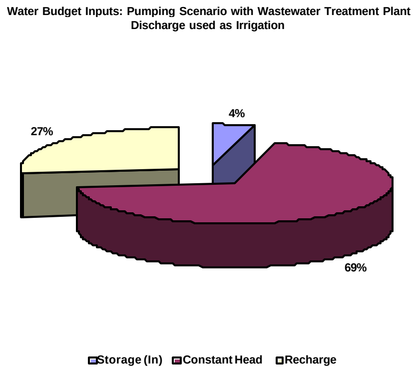


Figure 5. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being discharged directly into the environment in a natural channel.

<u>Management Objective 2:</u>

$P = N + xP + yP + zR$; where $x = 0\%$, $y = 25\%$, and $z = 0\%$





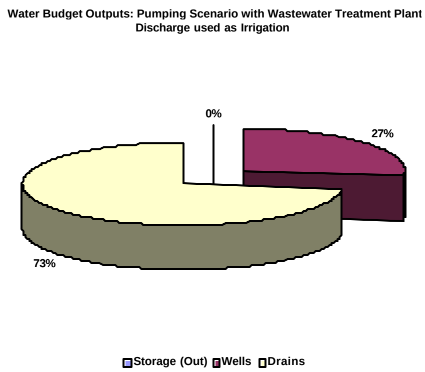


Figure 6. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being used to irrigate crops and lawns.

Management Objective 3:

P = N + xP + yP + zR; where x = 0%, y = 25%, and z = 10%

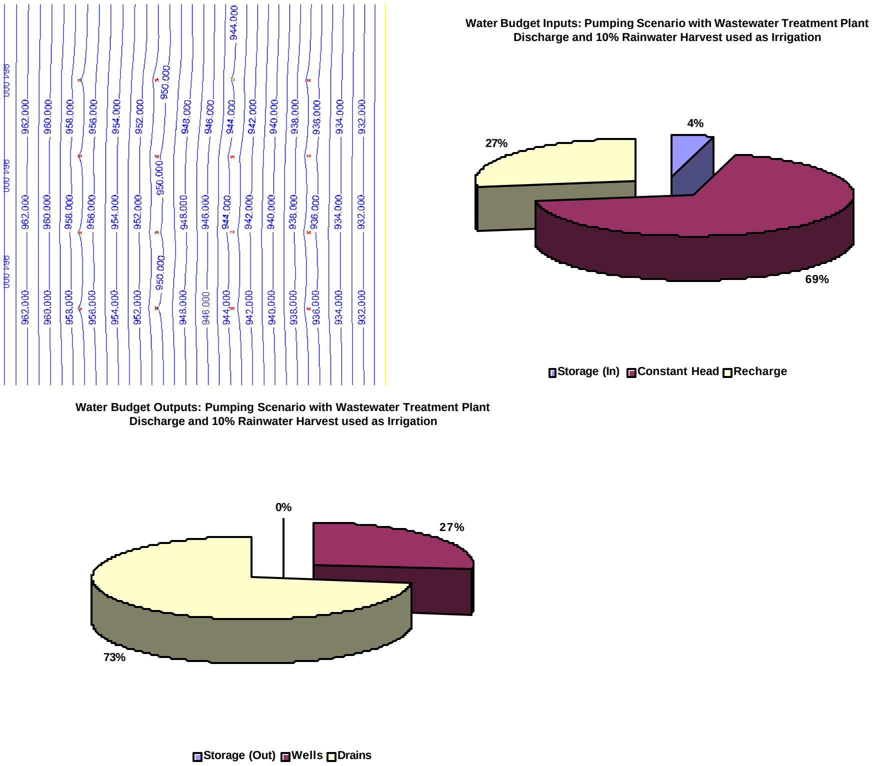
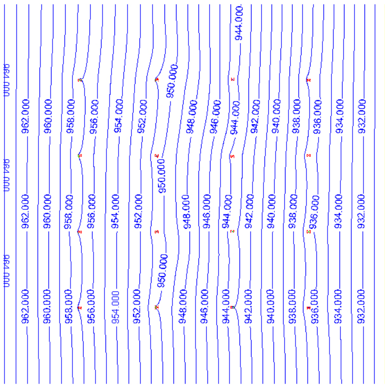
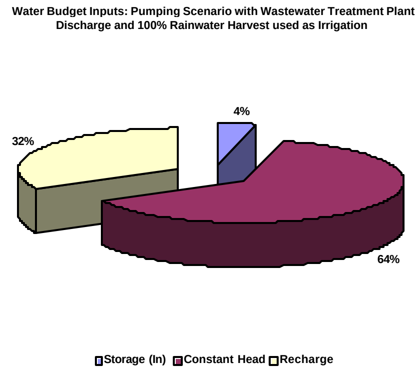


Figure 7. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 10 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

Management Objective 4:

P = N + xP + yP + zR; where x = 0%, y = 25%, and z = 100%





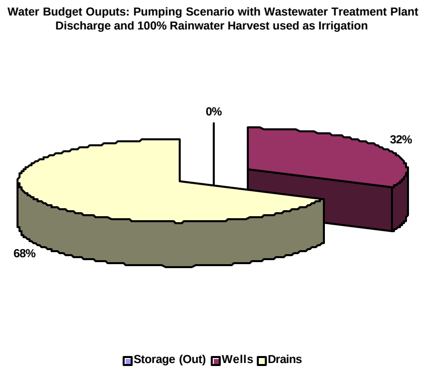
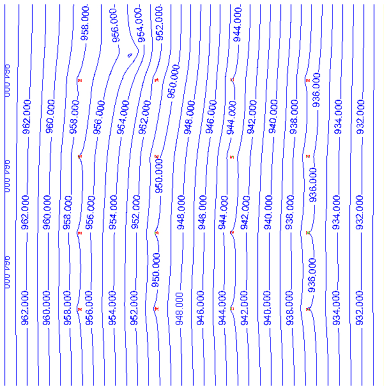
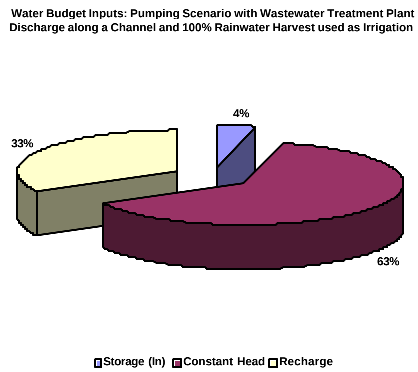


Figure 8. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 100 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

<u>Management Objective 5:</u>

P = N + xP + yP + zR; where x = 25%, y = 0%, and z = 100%





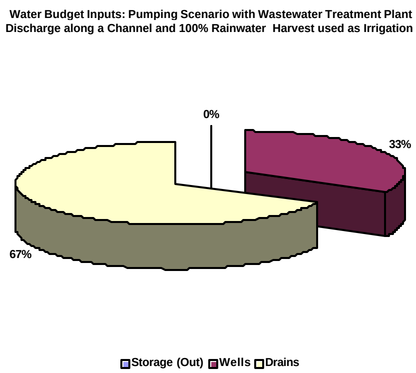
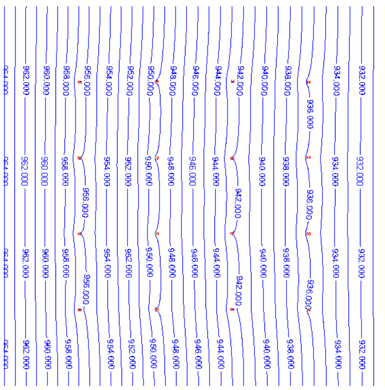
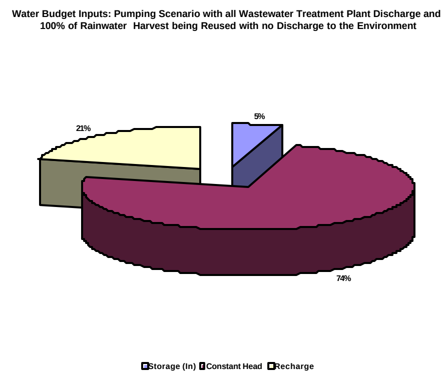


Figure 9. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being discharged directly into the environment in a natural channel, and with 100 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

Management Objective 6:

P = N + xP + yP + zR; where x = 0%, y = 0%, and z = 0%





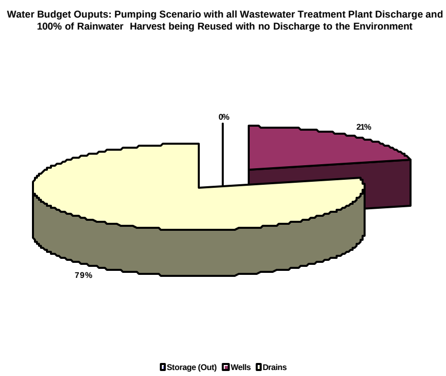


Figure 10. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 100 percent of precipitation falling on rainwater collection areas being reused without being discharged back into the environment.

Quantified Results of Conservation Measures

Table 4. Quantitative differences in water budget values between different numerical groundwater management models for a generic basin-fill aquifer in Arizona.

Scenario	Total Volume of Water (m^3) into Aquifer after 100 Years			Total Volume of Water (m^3) Out of Aquifer after 100 Years		
	Storage	***Constant Head***	***Recharge***	***Storage***	***Wells***	***Drains***
Natural	3.20×10^7	4.65×10^8	1.61×10^8	2109.3	0	6.60×10^8
Management Objective 1: *P = N+ xP+ yP+ zR; x = 25% y = 0% z = 0%*	3.39×10^7	5.36×10^8	2.12×10^8	6298.5	2.12×10^8	5.71×10^8
Management Objective 2: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 0%*	3.38×10^7	5.45×10^8	2.12×10^8	1671.0	2.12×10^8	5.80×10^8
Management Objective 3: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 10%*	3.38×10^7	5.45×10^8	2.18×10^8	1775.2	2.18×10^8	5.80×10^8
Management Objective 4: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 100%*	3.36×10^7	5.44×10^8	2.77×10^8	1694.7	2.76×10^8	5.79×10^8
Management Objective 5: *P = N+ xP+ yP+ zR; x = 25% y = 0% z = 100%*	3.38×10^7	5.34×10^8	2.77×10^8	22312	2.76×10^8	5.68×10^8
Management Objective 6: *P = N+ xP+ yP+ zR; x = 0% y = 0% z = 0%*	3.4×10^7	5.45×10^8	1.58×10^8	1669.9	1.58×10^8	5.79×10^8

Task 4:

Based on the results of the generic modeling of Task 3, we applied the potential conservation measures and alternative water supplies to a site specific numerical groundwater flow model. The model was constructed as the result of earlier studies (Wilson 2000, Kessler 2002) and modified to simulate conservation measures and alternative water supply impacts.

As part of the Tusayan Growth Environmental Impact Statement, a numerical flow model was built to project potential impacts to springs from 1989 to 1999, and potential future pumping of groundwater due to the proposed development (Montgomery and Associates 1999). A digital geologic framework model and a numerical groundwater flow model were constructed by Wilson (2000) and coupled with conceptual ecosystem and cultural information to characterize the impacts of groundwater withdrawals from this regional aquifer (Springer and Wilson 2000). Wilson (2000) delineated capture zones of the three major springs which discharge nearly 99 % of the water from the aquifer to determine which portions of the aquifer were influenced by which proposed wells. The conceptual ecosystem and cultural information were used to assess impacts of the changes in spring discharge on ecosystems and significant cultures.

Spring discharge from the three major springs is estimated to be 1,830 l/s from Havasu Springs, and 19 l/s each from Hermit Springs and Indian Garden Springs (Montgomery and Associates 1999). Total discharge from 17 minor springs is about 35 l/s (Kessler 2002). There are approximately another 60 springs with unmeasurable discharge (Kessler 2002). Thus, the total discharge out of the springs of the Redwall-Muav aquifer of the Coconino Plateau is about 1,900 l/s. About 97 % of the total discharge from the aquifer discharges to one spring complex, Havasu Springs.

While volumes of spring discharge from the aquifer are known with a relatively high degree of certainty, little else is. There are only about ten wells and a few other boreholes to describe the subsurface geology. There is only one specific capacity test (no constant-rate aquifer tests) from one well to measure aquifer properties. Although the rocks are marginally deformed tectonically and likely have significant dissolution enhancement, there are no subsurface measurements of this away from outcrops below the South Rim. There are no continuous records of water levels in wells to describe climatic and seasonal fluctuations. Because of the lack of data, Wilson (2000) built digital geologic framework models to help conceptualize and visualize the aquifer. These digital geologic framework models were updated and revised in this study and used to construct three-dimensional conceptual and numerical groundwater flow models (Kessler 2002).

Kessler (2002) constructed a model using the numerical code MODFLOW (Harbaugh and others 2000) to simulate the 3 major springs and 17 minor springs for steady-state, pre-pumping (pre-1989) conditions. Changes in discharge from the springs were assessed for transient pumping conditions from 1989 to 2002. Capture zones were delineated for all of the springs with the advective particle-tracking postprocessor for use with MODFLOW, MODPATH (Pollock 1994). Groundwater Vistas (Environmental Simulations Inc. 2003) was used as a pre- and post-processor for all modeling.

The spatial framework was imported from the digital geologic framework model (Kessler 2002). The groundwater model grid was created with 500 m square model grid cells so that each of the 20 springs below the South Rim of the Grand Canyon was simulated in individual model cells. The grid was rotated N60W so that the y-axis of the model grid coincided with the primary direction of groundwater flow, which is toward the northwest, and to the assumed principle direction of anisotropy of aquifer parameters along major fault and fracture zones. Because monoclines likely play an important role in the flow of groundwater before it infiltrates to the fracture- and conduit-flow dominated Redwall-Muav aquifer, the overlying Supai Group was simulated as a leaky, upper confining layer. The underlying Bright Angel Shale was assumed to be the lower confining layer for the model and was assumed to be a no-flow boundary. Therefore, the model had two layers, the Redwall-Muav aquifer and the Supai Group.

The model utilized specified-flow and head-dependent boundary conditions. Specified-flow boundaries of no flow were used to simulate the bottom of the model and the lateral hydrologic boundaries of the modeled region. These lateral no-flow boundaries were the Toroweap-Aubrey fault system to the west, the ill-defined groundwater divide with the adjoining Verde River groundwater basin to the south, the combination of the Mesa Butte Fault, East Kaibab Monocline, and the Grandview-Phantom Monocline to the east, and the escarpment of the South Rim to the north (Figure 1).

Recharge to the aquifer was also simulated with a specified-flow boundary condition. For the pre-development, steady-state model, the aquifer was assumed to be in a state of equilibrium, meaning that the amount of recharge to the aquifer was equal to the total amount of average discharge from springs in the Grand Canyon, 161,586 m^3/d. This represents about two percent of average annual precipitation, or about 8 mm per year. A zone of high recharge was applied around the fault zones, or zones of high hydraulic conductivity. This zone received 70 % of the recharge, while the rest of the recharge was distributed evenly over the remaining non-fractured areas of the model.

A final type of specified-flux boundary was to simulate pumping from wells. There were no pumping wells in the aquifer prior to 1989, so pumping stresses were only applied to the transient model. Pumping rates for the transient model were based on maximum well yields reported on the drillers well logs and do not represent actual rates at which the wells were pumped from 1989 to 2002 (Montgomery and Associates 1999).

Springs were simulated with a head-dependent boundary condition. Target flux values were determined from field measurements taken at the spring, or, in the case of inaccessibility to a spring or other logistical constraints, historical measurements of discharges (Montgomery and Associates 1999, Kessler 2002). Elevations of the springs were known with a fair degree of certainty, but the conductivity values of the springs were derived through the calibration process.

Property values were assigned based on measured values and literature values (Montgomery and Associates 1999; Wilson 2000). Four zones of hydraulic conductivity were applied to the two model layers. The zones represented the upper leaky Supai Group, matrix flow in the Redwall-Muav (lowest value), fracture flow in the Redwall-Muav (intermediate value), and major fault flow in the Redwall-Muav (highest value). The location of fault and fracture zones were modified from those of Montgomery and Associates (1999)(Figure 3). Porosity and storage zones mimic those of hydraulic conductivity.

The model was calibrated to measurements of water levels from nine wells and discharge measurements from the 20 springs. Water-level measurements only exist from the date the wells were drilled, and are at best only estimates of the steady-state condition of the aquifer. The residuals of hydraulic head at these wells were simulated to be within 5 to 10 % of the ratio of root mean squared error to total head change across the model (Anderson and Woessner 1992).

Because spring discharge measurements were more frequent in time and space than the water-level measurements in wells, they were assumed to be more accurate for calibration than water levels. The differences between simulated and observed spring discharges in the steady-state model were less than 5 % of the total observed spring discharge. There was no calibration of the transient simulation because of the lack of transient measurements of water levels in wells and transient measurements of spring discharge. Therefore, the transient simulation is only a predictive scenario. The changes in spring discharge for the large springs predicted by the transient model were similar to the changes predicted by the model created for the Tusayan Growth EIS (Montgomery and Associates 1999), but Kessler (2002) was the first study to predict changes in discharge for the small springs.

The transient simulation predicted decreases in discharges of 4 and 34 % from Hermit and Indian Garden Springs, respectively, and between 2 and 100 % decrease at nine of the smaller springs in the vicinity of Grand Canyon Village (Table 3). Havasu Springs discharge is predicted to decrease by 1.8 %, but accommodate nearly 80 % of the total volume of flow decrease (Table 3). Although accurate measurements of the quantities of decreased discharge predicted by the model have not been measured at all of the springs, there have been observed decreases in discharge at Cottonwood Spring which has been instrumented since 1994. Additional studies are being conducted to document decreases in flow at these smaller springs.

In general, the highest hydraulic heads are to the groundwater divides to the east, south and west and the lowest hydraulic heads are in the vicinity of the springs (Figure 4). Hydraulic head contours form “v” patterns which point up hydraulic gradient along the prominent fault and fracture zones. The capture zone analysis shows that most of the regional flow system is captured by the largest spring complex, Havasu Springs (Figure 5). All of the other springs have small capture zones with recharge areas located close to the South Rim. Because these springs have smaller capture zones, they are likely more influenced by short-term changes in climate and by local well pumping.

We collected discharge data for the Grand Canyon waste water treatment plant (WWTP) and the Tusayan WWTP. The Grand Canyon WWTP has been in operation during entire transient period of the model (1989-2002). Treated effluent from the WWTP discharges directly into an ephemeral stream channel located in the Bright Angel Fault zone. Average total annual discharge is approximately 190 ac-ft/yr. The Bright Angel Fault connects to Indian Gardens Springs at the South Rim.

The Tusayan WWTP has been in operation since 1992 (3 years into the transient simulation). Treated effluent from the WWTP is discharged into an ephemeral stream channel in the Vishnu Fault zone. Since 1992, total annual discharge has been approximately 70 ac-ft/yr.

We simulated additional recharge to the Grand Canyon regional flow model from the treated effluent from both the Grand Canyon WWTP and the Tusayan WWTP. We assumed that the total annual amount of effluent was available to recharge the aquifers along the two fault zones (Bright Angel and Vishnu).

The results of this modeling are preliminary and need more study after this project. Preliminary results indicate diminished decreases in discharge at Indian Gardens due to recharge from the Grand Canyon WWTP during the pumping scenario. Recharge from the Tusayan WWTP into the Bright Angel Fault zone indicates a delay in the diminishment of discharge of springs connected to this structure due to the recharge from treated waste water.

C. Principal Findings and Significances

Aquifer Storage

An examination of the generic numerical modeling results shows that the management scenario #6 caused significantly less water to come out of aquifer storage than any other management scenario. This is a result of the low limit on pumping set by the Safe Yield Policy (with no artificial recharge, pumping must balance natural recharge). Management scenario pulls slightly less water from storage than other scenarios; using WWTP discharge along with 100% of the rainwater harvest as recharge supplies pumping centers with enough water to reduce the volume pulled from storage.

Groundwater Divides

Management scenarios #1 and #5 pull less water from the constant head boundaries than scenarios #2, #3, #4, and #6. This suggests that discharging large quantities of water in a small area (directly from a WWTP, for example) can minimize the amount of water that is captured from adjacent watersheds. Spreading WWTP discharge over a larger area may lead to more significant shifts in the location of groundwater divides, as the reduced local recharge may not be large enough to counter the effects of pumping.

Pumping Rates

Management scenarios #4 and #5 allow for the largest volume of water to be pumped from the aquifer under Safe Yield conditions. Both of these scenarios utilized 100% of the rainwater harvest and 25% of WWTP effluent as recharge. There is no quantitative difference in the water budget between discharging WWTP effluent directly to the environment or distributing it over an irrigated area. Reducing the amount of rainwater harvest used significantly reduced the volume of artificial recharge. There was no significant difference between using 0% and 10% of the rainwater harvest as irrigation. Scenario #6 allows for the smallest volume of water to be pumped. It is easy to see why scenario #6 has the lowest limit for pumping; no rain or WWTP discharge recharges the aquifer, reducing allowable volume for pumping under the Safe Yield policy.

Spring Discharge

Management scenarios #1 and #5 result in lower spring discharges than scenarios #2, #3, #4 and #6. This suggests that discharging WWTP effluent directly to the environment can reduce spring flow when compared to distributing WWTP effluent across the study area as irrigation. This is because management scenarios which increase the amount of recharge may allow for greater amounts of pumping to achieve Safe Yield.

Management Considerations

If a water management scheme is optimized to provide maximum pumping rates, using waste-water treatment plant effluent as irrigation is the best scenario; the more effluent used to recharge the aquifer, the more groundwater can be pumped out again. However, discharging effluent directly to the environment causes more dramatic shifts in regional groundwater flow patterns than distributing effluent across a larger irrigated area. These shifts become more complex in management scenarios that demand seasonal variation in discharge volumes.

If a water management scheme is optimized to provide for the lowest reduction in spring flow while operating in a Safe Yield mode, using both WWTP effluent and rainwater harvest is the best scenario. Varying the percentage of rainwater harvest used as irrigation caused only a slight change in spring flow; the volume of wastewater treatment plant effluent dominated the model.

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